# PERFORMANCE ANALYSIS OF LOW RATE WIRELESS TECHNOLOGIES FOR MEDICAL APPLICATIONS

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**Abstract** - In this article we discuss what wireless technologies can be used for medical applications and how well they perform in a healthcare/hospital environment. We consider the emerging low-rate Wireless Personal Area Network (WPAN) technology as specified in the IEEE 802.15.4 standard and evaluate its suitability to the medical environment. We focus on scalability issues and the need to support tens of communicating devices in a patient's hospital room. We evaluate the effect of packet segmentation and backoff parameters tuning to improve the overall network performance that is measured in terms of packet loss, goodput, and access delay.

**Keywords** –Medical Applications, ECG, WPAN, Healthcare systems, performance analysis, medium access control.

## I. INTRODUCTION

In medicine, providing timely access to complete patient information is key to saving lives and improving the overall safety of a patient's care. While better recording and reporting systems have been developed to provide a wealth of healthcare data, the information remains fragmented and largely inaccessible. Even within hospitals and large medical groups, when patients see multiple providers in different settings, no one seems to have access to complete information.

While many hospitals today are in the early stages of using data from all of the patient connected medical devices, connections are mainly based on the RS-232 port interfaces that are made permanently to stationary monitors. In addition to the wiring cost to plug more devices on the network, there are severe incompatibility issues where each device manufacturer defines its own data link communication method. Therefore, proprietary drivers have to be loaded every time a different device is plugged into the network, making it unrealistic to plug in mobile devices several times during the day. In this context, there is a need for a universal or even a wireless, interface that provides connectivity, untethered access to information, and replaces the "hard-wired" approach. Closing the gap on the network connectivity and scalability issues affecting the medical environment is poised to become a major effort in revamping the current healthcare system and making it more efficient.

The IEEE 1073 working group is currently developing standard specifications for medical device communication focusing on wireless technologies that are adequate to the clinical domain and the patient's bedside. The main objective for this effort is to develop a universal and interoperable interface for medical equipments, that is (1) transparent to the end user, (2) easy to use, and (3) quickly (re)configured. The purpose of the group is not so much to develop new technologies, but to evaluate the suitability of current available technologies in the medical space.

In this article, we consider the IEEE 802.15.4 standard [1] that is a likely candidate for low bit rate WPAN applications, given the low bandwidth, low power requirement of most patient bedside devices. We evaluate the performance of a network consisting of several communicating devices in a patient's hospital room and stress the scalability and performance trade-offs that exist. Our objectives are to answer a number of questions concerning the performance and operation of a WPAN in a medical environment, for example the following: How many devices can be plugged into a WPAN? What is the performance achieved? What protocol parameters can be tuned to improve performance? The remainder of this article is organized as follows. Section II discusses the medical environment application requirements. In section III we give a brief overview of the IEEE 802.15.4 protocol specifications. In section IV, we consider realistic scenarios to discuss performance trends and trade-offs. In section V, we offer some concluding remarks.

## II. MEDICAL ENVIRONMENT REQUIREMENTS

Medical environment requirements have life or death implications when data is lost, corrupted, or delayed. This is unlike most other environments where these types of requirements are mainly financial.

The medical environment itself can produce harmful effects when considering the numerous medical devices that are present. Examples of these critical applications are the delivery of the correct medicine in the correct dosage at the correct time; the delivery of critical monitoring information in real time for trend calculations in determining alarm situations; and the distribution of a patient's information.

Electrocardiogram (ECG) monitoring is a medical application that consists of attaching electrodes to a person's body and connecting these via cables to a recording device. The analog signal recorded can be digitized using different methods. The result is a digital stream, which may be sent to a personal computer (PC) or a personal data/digital assistant (PDA). Some ECG sampling rates, sizes of sample, and numbers of leads are shown in Table 1

Table 1
ECG Data Information.

| | Value |
|---|---|
| Number of leads | 2-32 |
| Samples per lead per second | 200 to 500 |
| Sample size (bit) | 8, 16, 32 |
| End to end delay (s) | 2 |
| Bit error rate (BER) | $10^{-4}$ |

Collecting, storing, and transmitting these samples may vary based on the facilities available. Other applications such as blood analysis samples and supervisory, alarms, and status messages have smaller and less frequent sampling.

## III. LOW RATE WPAN FOR MEDICAL APPLICATIONS

The use of various wireless technologies for medical applications already exists (e.g., Wireless Local Area Network (WLAN) for Internet access and file sharing). However as time and technology progresses, so too does the infiltration of wireless into other areas and medical applications.

Cable replacement for removing tethering devices or to avoid tripping hazards appears to be a good reason for applying wireless technologies to medical applications.

We examine the new low rate IEEE Std. 802.15.4-2003 and its application to low rate medical applications.

The IEEE Std. 802.15.4 describes a very low rate wireless technology that is designed for communication among wireless devices within a short range of each other, using very low power (most likely battery operated) and with low data rate requirements.

The WPAN that is created when using this technology may be classified in one of two types: unslotted or slotted. For the unslotted WPAN all devices are considered peers with respect to one another and the entire wireless resource is available. For the slotted WPAN a structure is imposed on the wireless resource. This structure is shown in Figure 1.

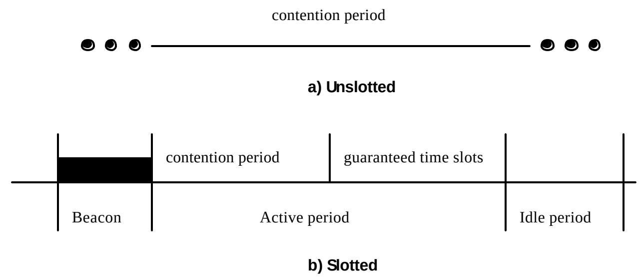


Figure 1 WPAN structure of wireless resource.

Within this structure are potentially three time periods. The first is for the sending of the beacon frame. The two beacon frames bound this structure. The second is the period directly following the beacon frame. This second period may be considered the active portion of the structure because it is during this time period when transmission and receptions may occur. This second or active time period may be further divided into a contention period and a non-contention period. During the contention period all devices are considered peers and compete equally for the resource using a Carrier Sensed Multiple Access with Collision Avoidance (CSMA/CA) mechanism. During the non-contention period resources can be allocated for use on a per device basis. The third period, if it exists, is an idle period when nothing is expected to be transmitted or received. This permits power savings while still maintaining synchronization with the beacon and a bound on delay.

As with most IEEE 802 standards, the 802.15.4 standard defines a physical layer and a medium access control (MAC) sublayer.

The physical layer defines three medium dependent wireless raw data rates covering three different frequency bands. These are 20, 40, and 250 kbit/s using the 868-868.6, 902-928, and 2400-2483.5 MHz frequency bands, respectively. In these respective frequency bands there are one, ten, and sixteen channels at these rates.

The MAC sublayer defines two CSMA/CA mechanisms, one for use in each of the two types of WPANs. Each have a number of default parameters that control the CSMA/CA process. For example the backoff exponent parameter bounds the range (from which a random value is selected) of the delay on how often an attempt is made to sense the wireless medium, and the maximum number of CSMA/CA backoffs parameter determines the number of attempts to sense the wireless medium for an idle condition before declaring a failure to transmit that particular frame.

We study only the unslotted WPAN when using the 2450 MHz band for a number of reasons. The 2450 MHz band provides the most channels (i.e., 16) at the highest data rates. The unslotted WPAN has the least overhead (i.e., no beacon frames). Based on the increased complexity for the slotted WPAN when compared to the unslotted WPAN, it is believed that the first devices available will have these characteristics.

## IV. PERFORMANCE EVALUATION RESULTS

We present simulation results to evaluate the performance of low-rate WPAN in a healthcare environment. Our simulation environment is based on detailed MAC, PHY and channel models for IEEE 802.15.4 (low-rate WPAN). The channel model consists of a geometry-based propagation model for the signals, as well as a noise model based on Additive white Gaussian noise (AWGN). For the indoor channel, we apply a propagation model consisting of two parts: (1) line-of-sight propagation (free-space) for the first 8 meters, and (2) a propagation exponent of 3.3 for distances over 8 meters [2]. We develop models for the low-rate WPAN access protocols using the OPNET [1,2] network simulator and configure the applications available in the simulator library.

In general, we find that performance results vary according to the network configuration, usage scenario and application considered [3]. In this article, we focus on two experiments that demonstrate the suitability of the IEEE 802.15.4 standard specifications to a healthcare/ medical environment. The first experiment focuses on scalability and the performance of the IEEE 802.15.4 technology in a multi-point to point topology, where multiple transmitters are communicating with a single receiver. The second experiment stresses the effect of tuning the backoff parameters of the IEEE 802.15.4 protocol on the network performance.

We first describe the application and scenarios used before discussing the results obtained. For WPAN, we consider a patient monitor where the ECG uses multiple leads that produces a 1500 byte frame every 0.25 s, the blood analysis produces a 1024 byte frame every second, supervisory control produces a 512 byte frame every second, and a 384 byte frame containing status or alert information every minute. The parameters used in the simulations are summarized in Table 2.

Table 2
Simulation Parameters.

| **Applications** | |
|---|---|
| Alarms & status | 384 Byte/60s |
| Supervisory & Control | 512 Byte/s |
| Blood analysis | 1024 Byte/s |
| ECG | 1500 Byte/ 0.25 s |
| **WPAN** | |
| Transmitted power (mW) | 1 |
| Packet header (bit) | 72 |
| Minimum Backoff Exponent | 3 (default) |
| Maximum Number of Backoffs | 4 (default) |
| Simulation Time (s) | 600 |

We use the configuration shown in Figure 2 that may be common to a hospital environment. It consists of a number of low-rate WPAN devices such as sensors communicating to a central node station.

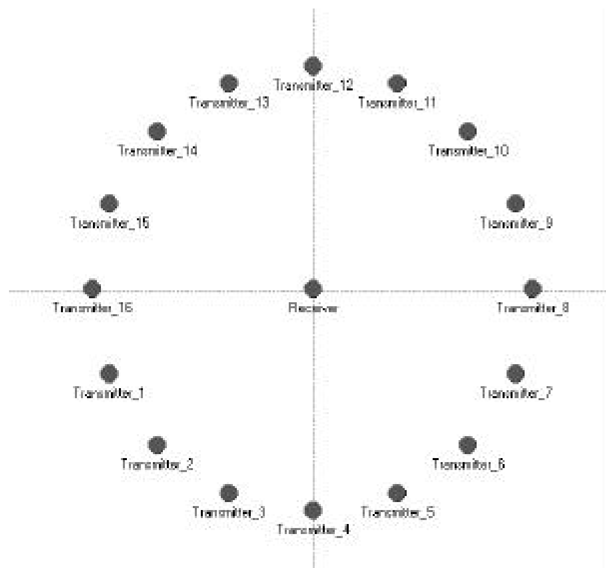


Figure 2 WPAN topology.

Each data point collected is averaged over 10 simulation trials using a different random seed for each trial. In addition to the mean value, we verify that statistical variation around the mean values are small and fall within a 95% confidence interval.

### *A. Experiment I: Baseline Results*

As shown in Table 2 this first set of performance results are based on the given applications without modifications and the defaults as stated in IEEE 802.15.4.

From Figure 3 we see that the packet delays are well within the medical requirements for delay, if this WPAN segment

[1] OPNET and OPNET Modeler are registered trademarks of OPNET Technologies, Inc.

[2] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

is considered the entire network. However, for the 1500 byte application this is deceiving, since the delay goes down as more transmitters are added. This is due to the way the application's data is sent and how the delay is calculated. Since the 1500 byte packet is too large for a single IEEE 802.15.4 MAC frame, multiple MAC frames (i.e., 16) are generated for each 1500 byte packet. All of these MAC frames are then queued, but once an error occurs in the transmission of one MAC frame (due to timeout or maximum retransmission attempts), then the remaining MAC frames are deleted from the queue as well.

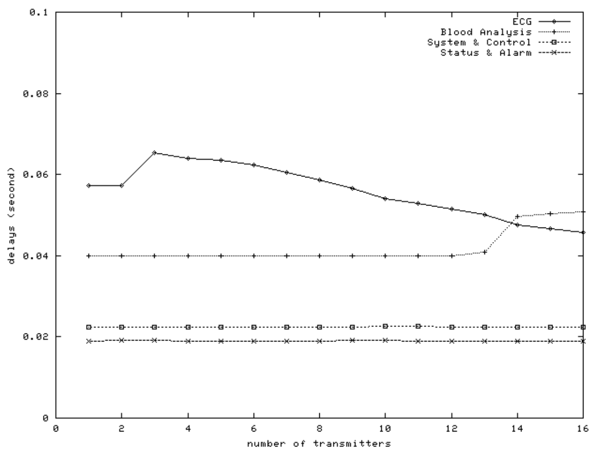


Figure 3 Delay as a function of number of transmitters.

From Figure 4 the effect of this is a dramatic decrease in goodput. The offered load on the WPAN reaches its maximum with just two devices. Adding just one more transmitter results in an overload of the WPAN's capacity. Due to the CSMA/CA mechanism when at least one of the MAC frames composing the application packet is lost, this results in an overall lower delay and goodput. Packet losses are shown in Figure 5 and Figure 6. Figure 5 shows the packet loss as seen by the application at the transmitter, while Figure 6 shows the MAC sublayer packet loss at the receiver. The difference in these two perspectives shows the likelihood that an application packet will be lost due to a loss of a single MAC frame in the attempt to access the wireless resource versus the likelihood to lose a MAC packet due to interference of another transmitter (i.e., collision). For the 1500 byte application (ECG) the bit error rate (BER) is unacceptable for three or more transmitters. For the 1024 byte application it takes thirteen transmitters to have an unacceptable BER. The other applications are not shown, since the number of transmitters studied is not large enough to produce enough load to cause packet loss.

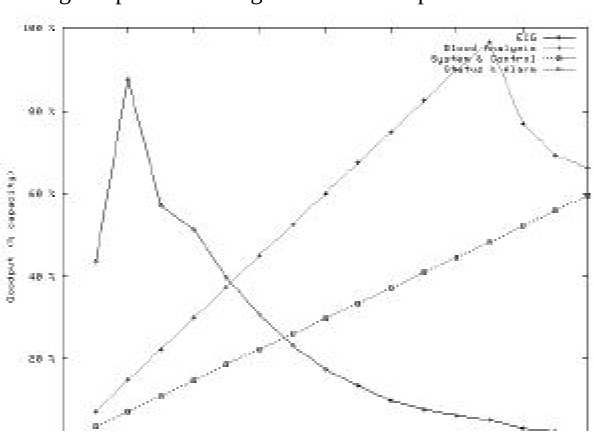


Figure 4 Goodput as a function of number of transmitters.

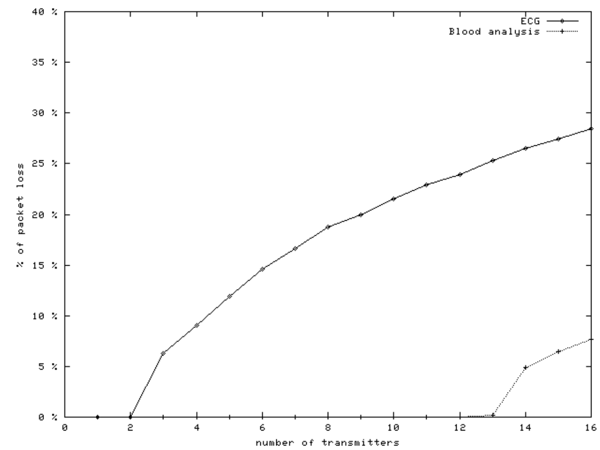


Figure 5 Percentage of packet loss as a function of number of transmitters.

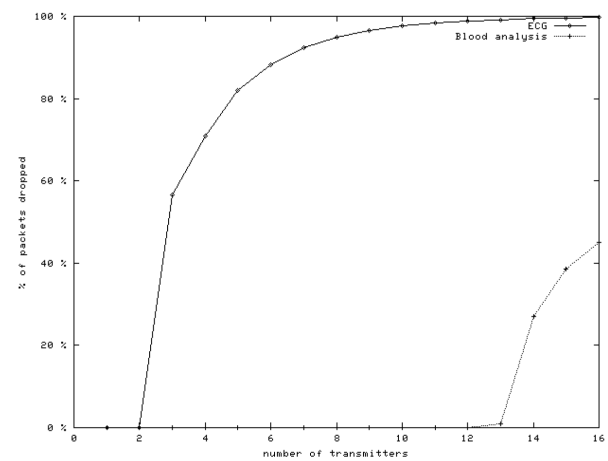


Figure 6 Percentage of MAC packet loss

### *B. Experiment II: Segmentation*

Based on the results obtained when using an IEEE 802.15.4 with default parameters with the given medical applications, it can easily be seen that there must be better parameter values, than the defaults and a better packaging of the medical applications, than using the current Ethernet framing. To this end we now show the results of various permutations.

Since the medical application using the Ethernet framing is obviously a remnant of the wired local area network, we decided to package the ECG samples into a single WPAN frame. This causes the MAC frames to be spaced out over a longer period, rather than a cluster of them at once. The number of MAC frames is approximately the same. This improves the goodput and packet loss as shown in Figure 7. However the delay is worse as is shown in Figure 8. This is expected given that the total aggregate network load is well beyond the capacity.

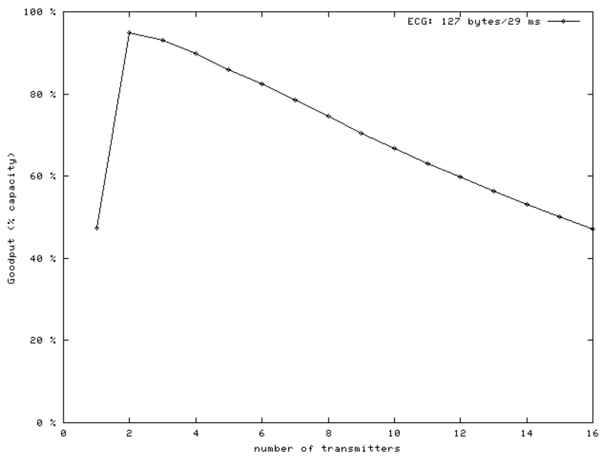


Figure 7 Goodput for new ECG packetization

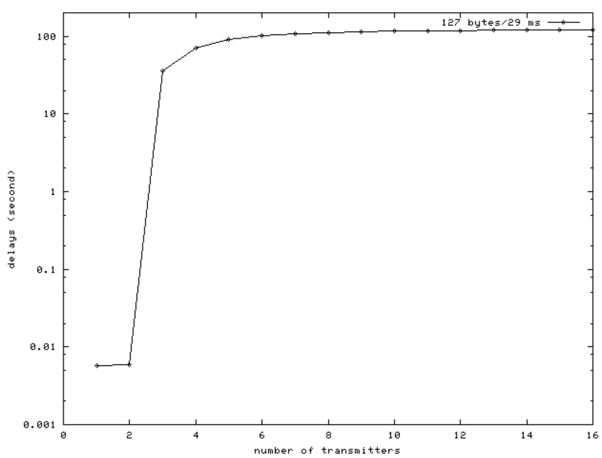


Figure 8 Delay for new ECG packetization

*C. Experiment II: Parameter Tuning*

Of course modifying every medical application to fit this particular, or for that matter any, wireless technology is not practical. We next investigate the performance of the given medical application (i.e, ECG) when different parameter values are used for the CSMA/CA algorithm. Only one parameter is varied while the defaults are used for the other parameters.

The maximum number of CSMA backoffs has a default of 4, but can vary from 0 to 5. This parameter is used to control the number of times a device will attempt to test the wireless resource for availability. Figure 9 shows the goodput results of this investigation. As one can see the default values are not the best selection. However, more interesting are the jagged curves, which did not smooth out over multiple or longer simulation runs. (See experiment III for further information)

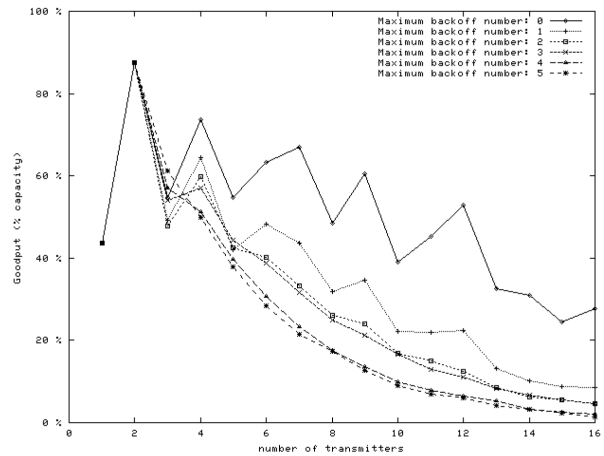


Figure 9 Goodput for 1500 byte/0.25s at various maximum CSMA/CA backoffs

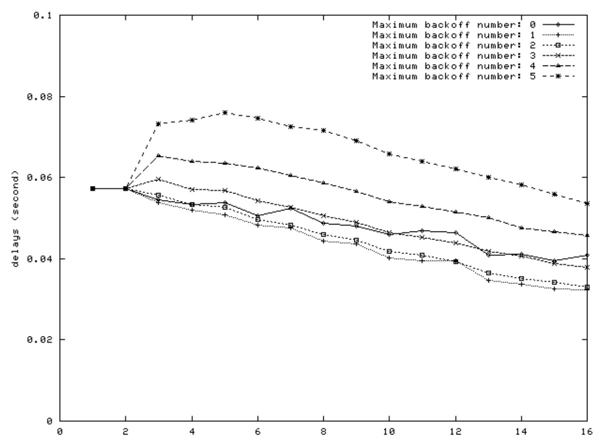


Figure 10 Packet delay for 1500 byte/0.25s at various maximum CSMA/CA backoffs

The minimum value for the backoff exponent has a default of 3 but can vary from 0 to 3. This parameter is used to control the range of possible random backoff slots before attempting to test the wireless resource for availability. Figure 11 shows the goodput results and Figure 12 shows the delay results of this investigation. As one can see here too, the default does not produce the best possible results.

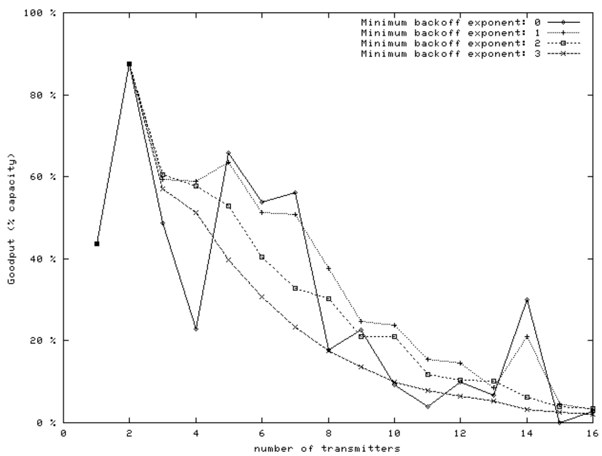


Figure 11 Goodput for 1500 byte / 0.25 s using various backoff exponent values

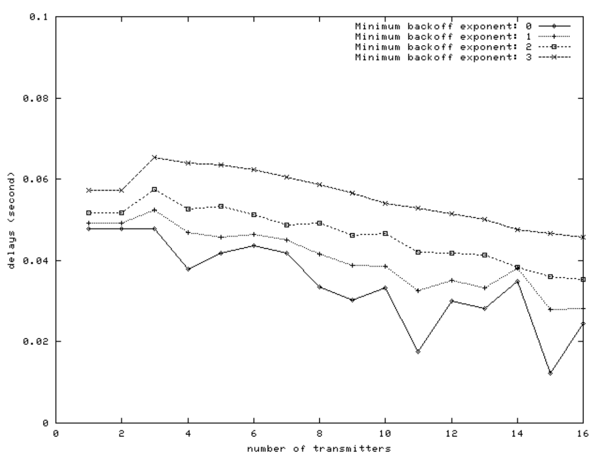


Figure 12 Delays for 1500 byte / 0.25 s using various backoff exponent values

*D. Experiment III: Exponential arrival*

From these experiments the jagged curves warrant further investigation to determine the origin of this apparent abnormality. Since the ECG medical application produces a constant and periodic stream of frames, changing the arrival of frames from constant to exponential is not applicable. However, using exponential arrivals does produce smooth curves (see Figure 13 and Figure 14). Thus we conclude that the randomness included in the CSMA/CA mechanism is not sufficient to avoid future synchronization of the competing devices' transmissions.

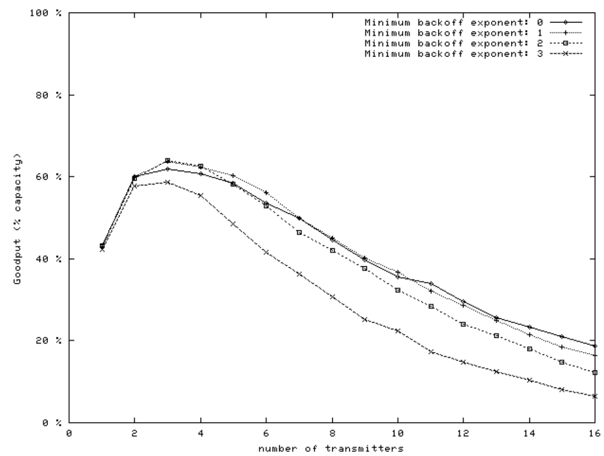


Figure 13 Goodput using exponential arrival at various backoff exponents

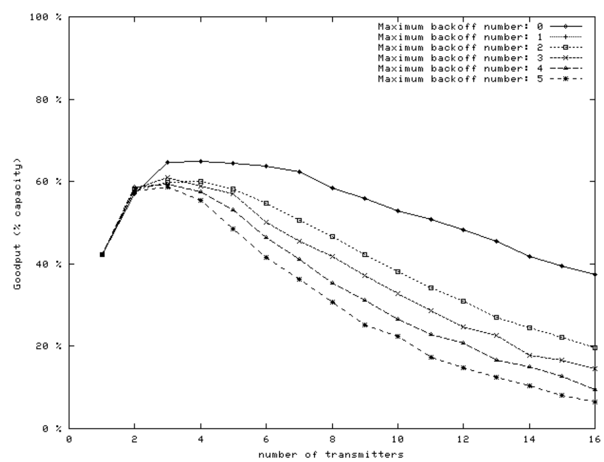


Figure 14 Goodput using exponential arrival at various maximum CSMA/CA backoffs

*E. Other Parameter Tuning for future work*

Other factors that may be used to change the performance are the size of the MAC frame, use of the unacknowledged data delivery mechanism, and a less persistent application.

From a strictly overhead point of view the best possible MAC frame size in the largest allowable (i.e., 127 bytes), which is what we studied. However this may not be optimal when other considerations are taken into account. Since the CSMA/CA mechanism uses a random backoff period before sensing the wireless medium, if a MAC frame is large, then it is highly likely that the sensing will occur during a frame's transmission. Thus at least another backoff period is required. This too may happen due to the same MAC frame and then depending on the number of backoffs, this can result in high packet drops, as can be seen in Figure 6.

In this article, we only study the acknowledged data delivery mechanism, which requires an acknowledgement from the receiver of the transmitted data frame that it was received. When this service is used the MAC layer will try for an extended period of time to transmit the data frame and receive the acknowledgement before declaring failure and dropping the frame. With the unacknowledged data service the MAC frame, once transmitted, is assumed to have succeeded. If this data service were used, it is expected that the delay will be lower and that number of packets dropped will be smaller.

## V. CONCLUDING REMARKS

In this article we investigate the use of the IEEE 802.15.4 standard specifications for medical applications in support of multiple devices with different data rates. Our findings can be summarized as follows.

The CSMA/CA mechanism built into the MAC protocol may limit the utilization of the medium. An aggregate data rate of 130% of the capacity from three transmitters leads to a goodput rate of little more than 50%. Furthermore, as the number of transmitters is increased to 16, the goodput rate drops to 5%.

We explore two different avenues to alleviate this scalability problem. First, we explore moving beyond the legacy Ethernet interface, and defining a segmentation of the application framing structure into smaller chunks that fit into IEEE 802.15.4 MAC packets. This approach improves the goodput rate up to 90% for two/three transmitters, and 40% for 16 transmitters. An obvious side effect for this method is that the access delay can grow significantly, proportionally to the aggregate network load.

Second, we look into tuning the backoff parameters that control the CSMA/CA mechanism. We observe that by increasing the transmission persistence, i.e. reducing the maximum backoff number and the minimum backoff exponent to 0, goodput is increased to 60% and 40% for two and 16 transmitters respectively. The main disadvantage of transmission persistence is a transmission synchronization problem exhibited by the sawtooth pattern in the goodput curve. We verify that this synchronization is mainly due to the constant nature of the application traffic used and note that the behaviour symptoms disappear for exponential packet generation distributions.

## AKNOWLEDGEMENTS

We wish to acknowledge the members of the IEEE 1073, especially Jan Wittenber, developing the technical report on RF wireless for medical devices. Without their help we would not have current medical application information.

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